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# SFTP Cycle Contributions to Light-Duty Diesel Exhaust Emissions

## INTERIM REPORT
## TFLRF No. 361

by
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**Southwest Research Institute™**
**San Antonio, TX**

for
**U. S. Department of Energy**
**Office of Transportation Technologies**
**1000 Independence Avenue, SW**
**Washington, D. C. 20585**

Under Contract to
**U.S. Army TARDEC**
**Petroleum and Water Business Area**
**Warren, MI 48397-5000**

Contract No. DAAE-07-99-C-L053 (WD 12)
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**June 2002**

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Approved by:

Edwin C. Owens, Director
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U.S. light-duty diesel exhaust emissions are determined for a given vehicle following the Supplemental Federal Test Procedure (SFTP). The SFTP consists of three test cycles: the chassis dynamometer portion of the FTP-75, US06 aggressive driving cycle, and SC03 air conditioning cycle. The objective of this investigation was to determine the relative contribution of each individual test cycle to each measured exhaust emission.

Based on the exhaust emissions data from the ligh-duty diesel powered vehicle used in this project, the following conclusions are made: While the SC03 air conditioning cycle is weighted at 37%, only 21% of the total PM emissions come from the SC03 cycle; 36% of the total Nox emissions are derived from this cycle. The relative importance of the SC03 contribution to total exhaust emissions can be illustrated by calculating the weighted emissions with and without the SC03 cycle. If only the FTP and US06 are considered (non air-conditioned vehicle) the total weighted NOx is 17% less than when the SC03 is included.

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## EXECUTIVE SUMMARY

U.S. light duty diesel exhaust emissions are determined for a given vehicle following the Supplemental Federal Test Procedure (SFTP). The SFTP consists of three test cycles: the chassis dynamometer portion of the FTP-75, US06 aggressive driving cycle and SC03 air conditioning cycle. The objective of this investigation was to determine the relative contribution of each individual test cycle to each measured exhaust emission.

Based on the exhaust emissions data from the light-duty diesel powered vehicle used in this project, the following conclusions are made:

- While the SC03 air conditioning cycle is weighted at 37%, only 21% of the total PM emissions come from the SC03 cycle; 36% of the total NOx emissions are derived from this cycle.
- The relative importance of the SC03 contribution to total exhaust emissions can be illustrated by calculating the weighted emissions with and without the SC03 cycle. If only the FTP and US06 are considered (non air-conditioned vehicle) the total weighted NOx is 17% less than when the SC03 is included.

## FOREWORD/ACKNOWLEDGMENTS

This work was performed by the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute™ (SwRI®), San Antonio, Texas, during the period September 2001 through December 2001 under Contract No. DAAE-07-99-C-L053. The work was funded by the U. S. Department of Energy Office of Transportation Technologies (DOE/OTT). The project was administered by the U.S. Army Tank-Automotive RD&E Center, Petroleum and Water Business Area, Warren, Michigan. Mr. Luis Villahermosa (AMSTA-RBFF) served as the TARDEC contracting officer's technical representative. Mr. John Garbak (DOE) served as the project technical monitor.

## TABLE OF CONTENTS


| Section | | | Page |
|---|---|---|---|
| I. | BACKGROUND/OBJECTIVE | | 1 |
| II. | APPROACH | | 1 |
| III. | TEST RESULTS | | 7 |
| | A. | PM and NOx Results | 7 |
| | B. | Volatile Organic Fraction (VOF) and Wet Sulfate Material Results | 9 |
| IV. | SUMMARY AND CONCLUSIONS | | 9 |
| V. | REFERENCES | | 10 |


## LIST OF TABLES


| Table | | Page |
|---|---|---|
| 1. | 2000 VW Jetta Turbodiesel Specifications | 2 |
| 2. | ECD-1 Diesel Fuel Properties | 3 |
| 3. | Test Results | 7 |


## LIST OF ILLUSTRATIONS


| Figure | | Page |
|---|---|---|
| 1. | SC03 Test Cycle | 4 |
| 2. | US06 Test Cycle | 4 |
| 3. | FTP Test Cycle | 5 |
| 4. | Front View of Vehicle Test Installation | 6 |
| 5. | Rear View of Vehicle Test Installation | 6 |
| 6. | Weighting factors for the three test cycles that define SFTP | 8 |
| 7. | Contribution of each test cycle to weighted PM exhaust emissions | 8 |
| 8. | Contribution of each test cycle to weighted NOx exhaust emission | 8 |

## ACRONYMS & ABBREVIATIONS

| | |
|---|---|
| CFR | Code of Federal Regulations |
| DFI | Director Filter Injection |
| EPA | Environmental Protection Agency |
| GC | Gas Chromatography |
| NOx | Oxides of Nitrogen |
| PM | Particulate Matter |
| SFTP | Supplemental Federal Test Procedure |
| SwRI | Southwest Research Institute™ |
| TARDEC | Tank-Automotive Research Development and Engineering Center |
| TACOM | Tank-Automotive Armaments Command |
| TFLRF | U.S. Army TARDEC Fuels and Lubricants Research Facility |
| VOF | Volatile Organic Fraction |
| VW | Volkswagen |

## I. BACKGROUND/OBJECTIVE

U.S. light duty diesel exhaust emissions are determined for a given vehicle following the Supplemental Federal Test Procedure (SFTP). The SFTP consists of three test cycles: the chassis dynamometer portion of the FTP-75, US06 aggressive driving cycle, and SC03 air conditioning cycle.(1)* The objective of this investigation is to determine the relative contribution of each individual test cycle to each measured exhaust emission. This information will be useful in defining appropriate emission control devices to be used for the reduction of exhaust emissions.

## II. APPROACH

A 2000 model year VW Jetta passenger vehicle powered by a 1.9L light-duty diesel engine with a manual 5-speed transmission was used for this investigation. Vehicle and engine properties are presented in Table 1. A low sulfur diesel fuel designated ECD-1 was used. The properties of ECD-1 fuel are presented in Table 2. Exhaust emissions and fuel economy were evaluated in triplicate over the Supplemental Federal Test Procedure (SFTP) for light-duty vehicles, which includes the chassis dynamometer portion of the FTP, the US06 aggressive driving cycle, and a modified version of the AC2 option of the SC03 air conditioning cycle. Figures 1, 2, and 3 illustrate the vehicle speed and duration for these three test cycles.(2) As given in the Code of Federal Regulations (CFR), the AC2 option does not include elevated temperatures or solar loading; however, there are stipulations for the control of temperature, humidity, and vehicle frontal airflow.(3) In order to conduct this work in a cost-effective manner, deviations from the AC2 test procedure were as follows:

*Underscored numbers in parentheses indicate references at the end of the document.

- Test cell temperature was targeted at 76 degrees F nominal, but was not necessarily maintained at ±2 degrees F on average and ± 5 degrees F instantaneous.
- Test cell humidity was targeted at 50 grains of water per pound of dry air, but was not necessarily maintained at ±5 grains of water per pound of dry air.
- A constant speed-cooling fan with nominal output of 5,000 cfm was used in front of the vehicle rather than a variable-speed fan. The fan discharge area is approximately 3.5 ft2.
- It is felt that this modified AC2 cycle would still sufficiently simulate the additional loading an engine experiences with the operation of the AC compressor, thus providing an indication of the additional NOx production expected during AC operation.

| **Table 1. 2000 VW Jetta Turbodiesel Specifications** | |
|---|---|
| **Vehicle, GLS, TDI** | |
| Curb Weight, lb | 3036 |
| Transmission, | 5-speed, manual |
| Air Conditioning | Yes |
| EPA Fuel Economy (City/Hwy) | 42/49 mpg |
| **Engine, Turbodiesel** | |
| Displacement, | 1.9L |
| Horsepower | 90 @ 3750 RPM |
| Torque, lb-ft | 155 @ 1900 RPM |
| Bore X Stroke, in | 3.13 x 3.76 |
| Compression ratio | 19.5: 1 |

| Table 2. ECD-1 Diesel Fuel Properties | | |
|---|---|---|
| AL No.: | | 26847F |
| Fuel I.D.: | | ECD-1 |
| Property | Method | |
| Density@15 C, kg/L | D-4052 | 0.8315 |
| Hydrogen, mass % | D-5291 | 13.490 |
| Carbon, mass % | D-5291 | 86.220 |
| Distillation by Volume | D-2887 | |
| IBP °C | | 122.5 |
| 10% °C | | 177.8 |
| 50% °C | | 256.2 |
| 90% °C | | 345.7 |
| 95% °C | | 368.2 |
| End Point | | 419.2 |
| Distillation by Volume | D-86 | |
| IBP °C | | 169.8 |
| 10% °C | | 205.7 |
| 50% °C | | 259.7 |
| 90% °C | | 326.1 |
| 95% °C | | 343.3 |
| End Point | | 353.9 |
| Cetane No. | D-613 | 52.8 |
| Cetane Index | D-976 | 51.8 |
| K. Viscosity @ 40 °C, cSt | D-445 | 2.41 |
| Flash Pt., °C | D-93 | 66 |
| Oxygen, wt. % | difference | 0.290 |
| Nitrogen, µg/g | D-4629 | 9 |
| Sulfur, ppm | D-5453 | 11 |
| Hydrocarbon Type, wt. % | | |
| Total Aromatics | D-5186 | 21.65 |
| Monoaromatic | D-5186 | 18.50 |
| Polyaromatics | D-5186 | 3.15 |
| Saturates | D-5186 | 78.36 |
| Paraffins, wt. % | D-2425 | NA |
| Naphthlenes, wt. % | | NA |
| Total Water , ppm | D-6304 | 88 |
| Color | D-1500 | 1.0 |
| Appearance | D-4176 | Pass, Brt/Clear |
| Particulates, mg/L | D-6217 | 1.54 |
| Cloud Pt., °C | D-5773 | -8.0 |
| Pour Pt., °C | D-5949 | -12.0 |
| TAN, mg KOH/g | D-664 | 0.13 |
| Net Heat of Combustion, MJ / kg | D-240 | 41.67 |
| Gross Heat of Combustion, MJ / kg | D-240 | 44.53 |
| HFRR Lubricity, µm @ 60C | D-6079 | 460 |
| BOCLE Scuff, grams | D-6078 | 3150 |

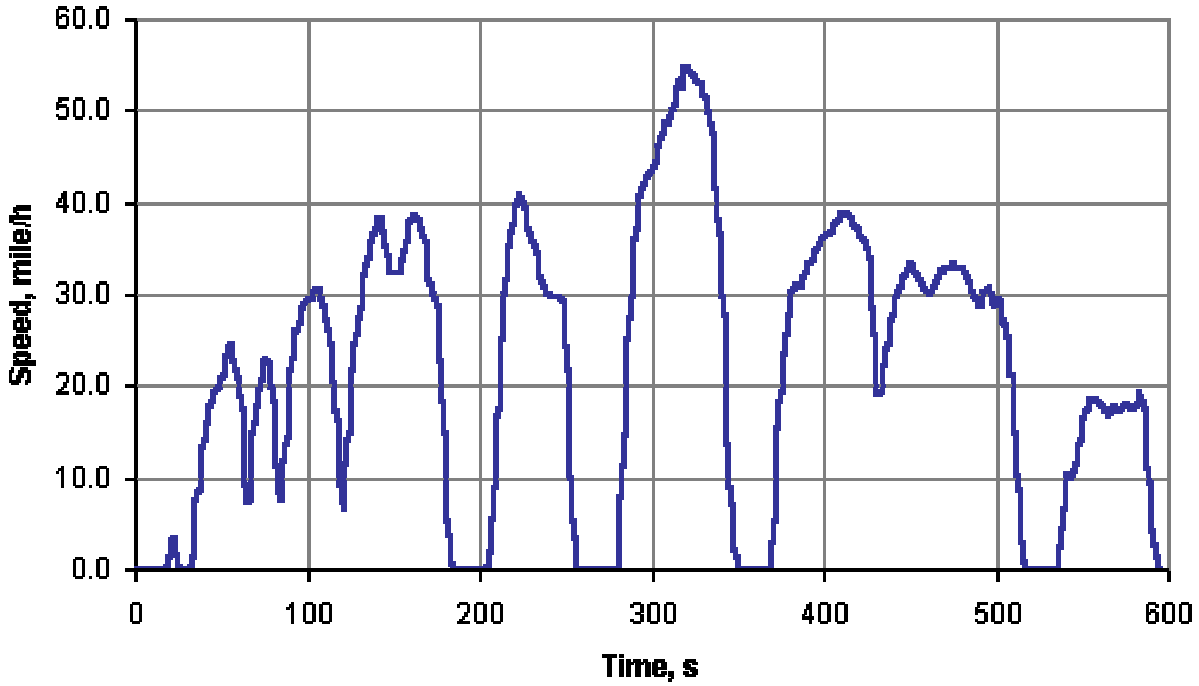


**Figure 1. SC03 Test Cycle**

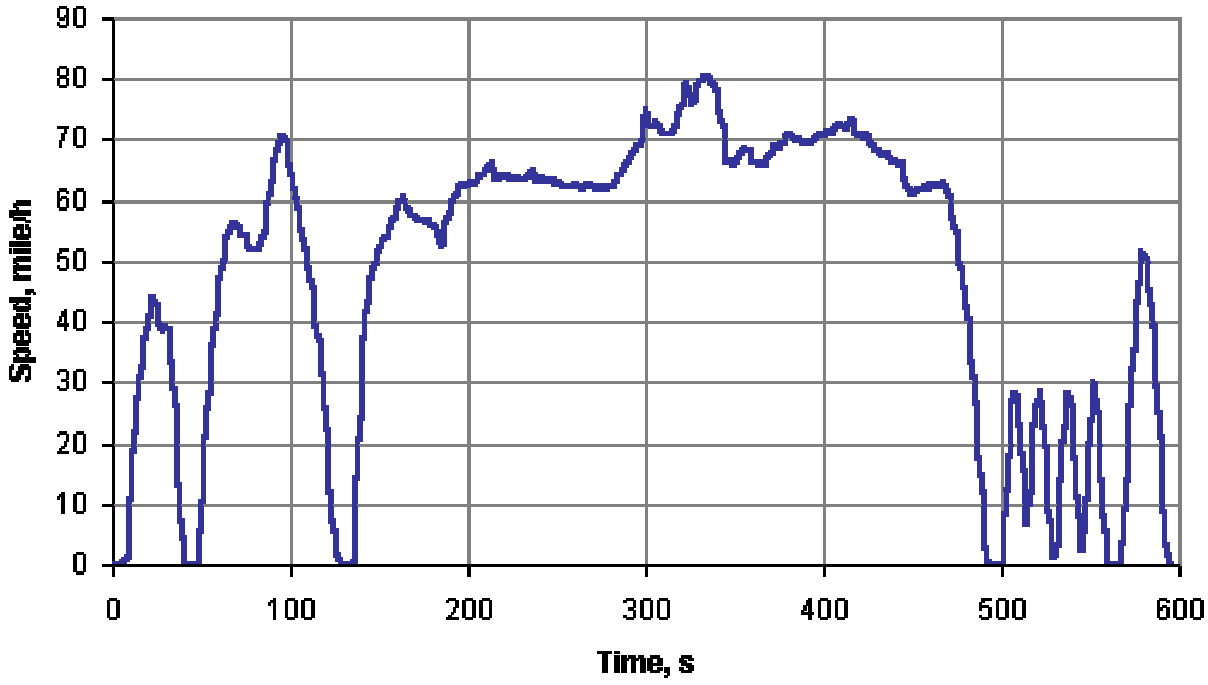


**Figure 2. US06 Test Cycle**

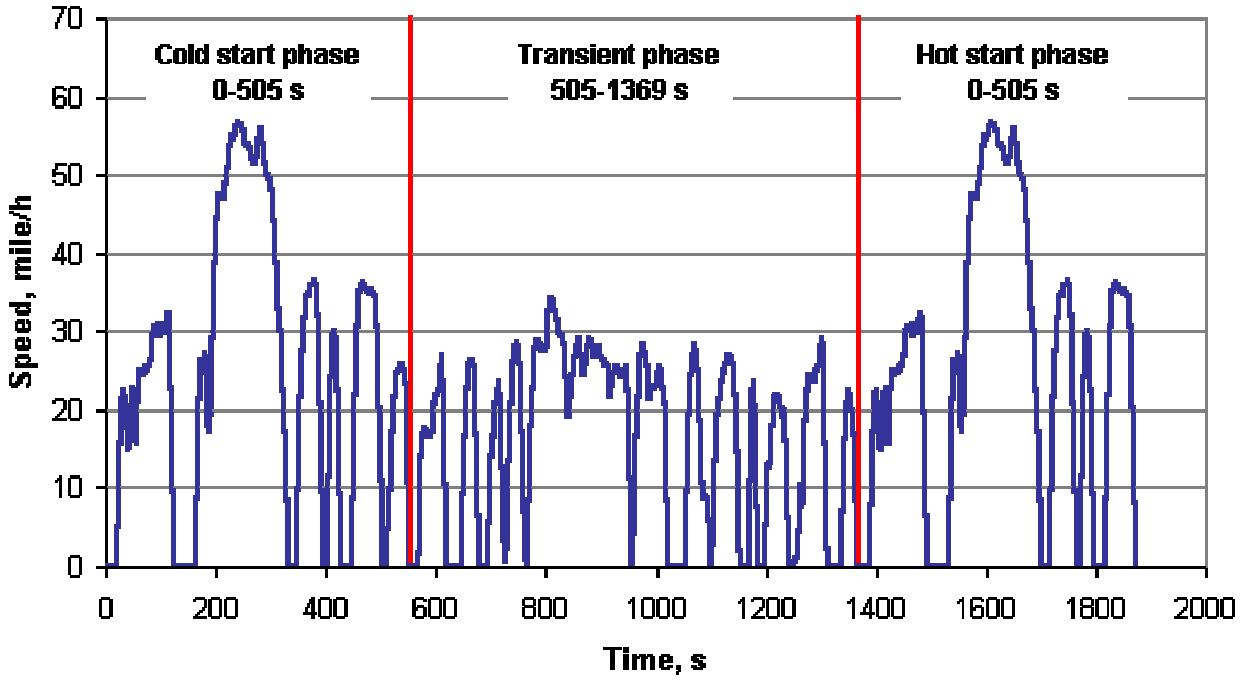


**Figure 3. FTP Test Cycle**

Regulated exhaust emissions (non-methane hydrocarbons, carbon monoxide, oxides of nitrogen, and particulate matter) and carbon dioxide were determined in a manner consistent with EPA protocols for light-duty emission testing as given in the CFR.(3) Proportional dilute exhaust gas samples were collected in Tedlar bags for analysis of carbon monoxide, carbon dioxide, and methane. Total hydrocarbons and oxides of nitrogen were measured continuously from the dilution tunnel. Concurrently, a proportional sample of the dilute exhaust was drawn through Pallflex T60A20 fluorocarbon-coated glass fiber filters for determination of particulate matter. Filter samples were analyzed by direct filter injection gas chromatography (DFI/GC) to determine the particulate volatile organic fraction (VOF) and lubricating oil contribution to VOF. Ion chromatography was used to determine sulfate fraction of particulate. Exhaust constituents were analyzed as specified below:

| Constituent | Analysis Method |
|---|---|
| Total Hydrocarbon | Heated Flame Ionization Detector |
| Methane | Gas Chromatography |
| Carbon Monoxide | Non-Dispersive Infrared Analysis |
| Carbon Dioxide | Non-Dispersive Infrared Analysis |
| Oxides of Nitrogen | Chemiluminescent Analysis |
| Particulate Matter | Gravimetric |
| Volatile Organic Fraction of PM | Direct Filter Injection Gas Chromatography |
| Oil Fraction of VOF | Direct Filter Injection Gas Chromatography |
| Sulfate Fraction of PM | Ion Chromatography |

Figures 4 and 5 show the front and rear view of the vehicle test installation, respectively.

**Figure 4. Front View of Vehicle Test Installation**

**Figure 5. Rear View of Vehicle Test Installation**

## III. TEST RESULTS

The results for the triplicate FTP, US06, and SC03 exhaust emission tests are presented in Table 3. The individual test data sheets are in Appendix A.

Table 3. Test Results

| | THC | CO | NOx | Total PM | Total PM | Wet Sufate* | VOF | Unburned | FE |
|---|---|---|---|---|---|---|---|---|---|
| | g/mi | g/mi | g/mi | g/mi | mg/mi | mg/mi | mg/mi | Oil, % | mi/gal |
| FTP-1 | 0.073 | 0.315 | 0.708 | 0.044 | 44.0 | 2.18 | 14.08 | 22% | 41.22 |
| FTP-2 | 0.057 | 0.290 | 0.724 | 0.055 | 55.2 | 2.35 | 17.14 | 30% | 40.37 |
| FTP-3 | 0.067 | 0.285 | 0.737 | 0.046 | 46.1 | 3.35 | 15.33 | 16% | 40.16 |
| AVG | 0.066 | 0.297 | 0.723 | 0.048 | 48.4 | 2.63 | 15.52 | 23% | 40.58 |
| | | | | | | | | | |
| SC03-1 | 0.012 | 0.017 | 1.124 | 0.063 | 63.2 | 1.79 | 14.87 | 15% | 34.38 |
| SC03-2 | 0.000 | 0.037 | 1.163 | 0.059 | 59.2 | 1.19 | 13.11 | 17% | 33.77 |
| SC03-3 | 0.012 | 0.046 | 1.172 | 0.053 | 53.2 | 0.91 | 16.26 | 19% | 33.80 |
| AVG | 0.008 | 0.033 | 1.153 | 0.058 | 58.6 | 1.30 | 14.75 | 17% | 33.98 |
| | | | | | | | | | |
| US06-1 | 0.002 | 0.024 | 1.816 | 0.276 | 276.4 | 89.69 | na** | na** | 39.48 |
| US06-2 | 0.000 | 0.015 | 1.744 | 0.216 | 216.2 | 80.91 | 8.82 | 7% | 40.64 |
| US06-3 | 0.000 | 0.003 | 1.701 | 0.190 | 190.3 | 64.49 | 9.51 | 5% | 40.71 |
| AVG | 0.001 | 0.014 | 1.754 | 0.227 | 227.6 | 78.36 | 9.16 | 6% | 40.28 |
| | | | | | | | | | |
| SFTP = 0.35*FTP + 0.37*SC03 + 0.28*US06 | | | | | | | | | |
| SFTP-1 | 0.031 | 0.123 | 1.172 | 0.116 | 116.2 | 26.54 | na** | na** | 38.20 |
| SFTP-2 | 0.020 | 0.119 | 1.172 | 0.102 | 101.8 | 23.92 | 13.32 | 19% | 38.00 |
| SFTP-3 | 0.028 | 0.118 | 1.168 | 0.089 | 89.1 | 19.56 | 14.04 | 14% | 37.96 |
| AVG | 0.026 | 0.120 | 1.171 | 0.102 | 102.4 | 23.34 | 13.68 | 16% | 38.06 |
| | | | | | | | | | |
| * - total includes "dry" sulfate plus associated water of hydration<br>** - data not available | | | | | | | | | |

### A. PM and NOx Results

Figure 6 shows the weighting factors for the three test cycles that define the SFTP. The contribution of each test cycle to weighted PM exhaust emissions is shown in Figure 7.(1) This illustrates that the majority of weighted PM exhaust emission is attributed to the US06 cycle. The contribution of each test cycle to weighted NOx exhaust emission is shown in Figure 8.

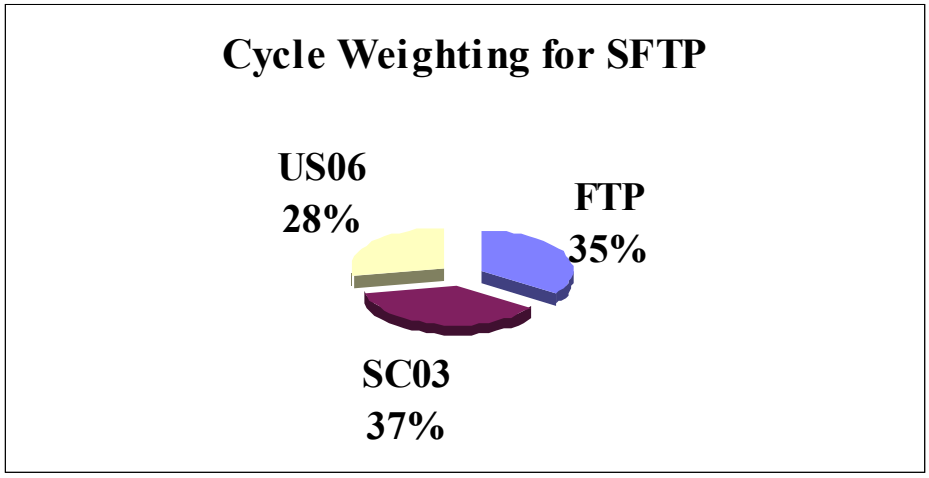


Figure 6. Weighting factors for the three test cycles that define SFTP

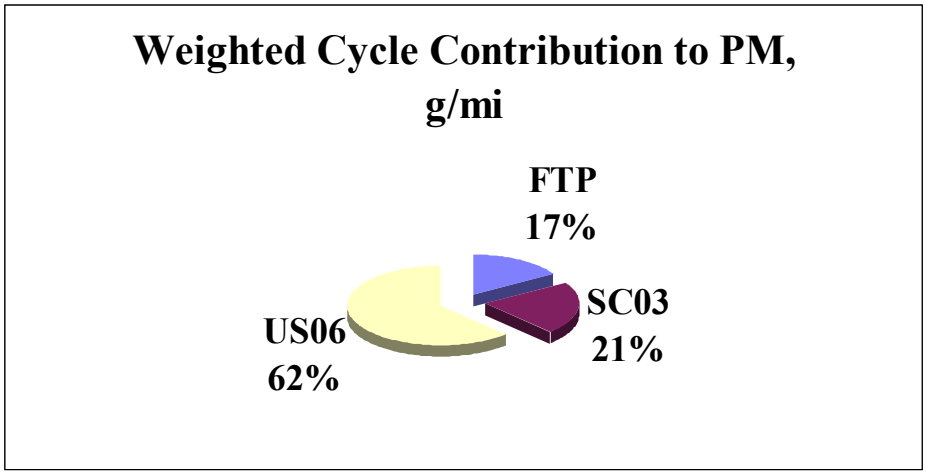


Figure 7. Contribution of each test cycle to weighted PM exhaust emissions

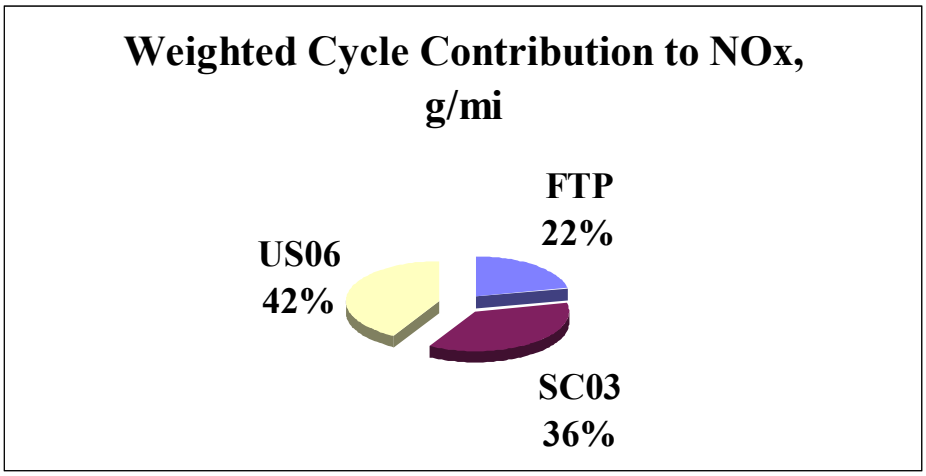


Figure 8. Contribution of each test cycle to weighted NOx exhaust emission

The formula for calculating weighted exhaust emissions for vehicles without A/C is SFTP=0.72 (FTP value) + 0.28 (US06 value). A comparison of SFTP values calculated with and without including the A/C cycle was made for this vehicle. If the A/C cycle is not included in the SFTP calculations, the values are 1.01 g/mi $NO_x$, and 0.098 g/mi PM. When the A/C cycle is included, the values are 1.17 g/mi $NO_x$, and 0.102 g/mi PM. The $NO_x$ values for this vehicle are approximately 16% higher when the SC03 cycle is included.

### B. Volatile Organic Fraction (VOF) and Wet Sulfate Material Results

The volatile organic fraction (VOF) of particulate matter was similar for the FTP and SC03 cycles, and approximately one third less for the US06 cycle. The unburned oil percentage of the VOF was highest for the FTP, intermediate for the SC03 and lowest for the US06 cycle. The majority of the wet sulfate material was produced during the US06 cycle.

## IV. SUMMARY/CONCLUSIONS

Based on the exhaust emissions data from the light-duty diesel powered vehicle used in this project, the following conclusions are made:

1. Because each of the three test cycles produce a unique cycle dependent set of exhaust emissions, the actual contribution of each test cycle is different than its weighting factor.

2. While the SC03 air conditioning cycle is weighted at 37%, only 21% of the total PM emissions come from the SC03 cycle; 36% of the total NOx emissions are derived from this cycle.

3. While the US06 cycle is weighted at only 28%, a full 62% of the total PM emissions and 42% of the total NOx emissions come from US06.

4. The relative importance of the SC03 contribution to total exhaust emissions can be illustrated by calculating the weighted emissions with and without the SC03 cycle. If only the FTP and US06 are considered (non air-conditioned vehicle) the total weighted NOx is 17% less than when the SC03 is included.

5. The vast majority of the wet sulfate material is produced during the US06 test cycle. The lowest VOF of PM and unburned oil portion of VOF were produced during the US06 test cycle.

## V. REFERENCES


1. Federal Register, Vol. 61, No. 205, October 22, 1996, Rules & Regulations, p. 54855.

2. http://www.epa.gov/oms/emisslab/methods

3. Code of Federal Regulations 40, Part 86, Subpart B, Revised July 2001.